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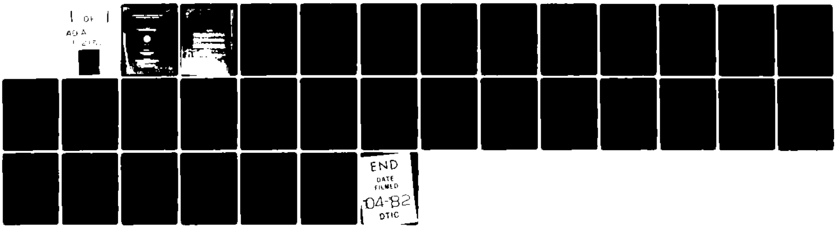
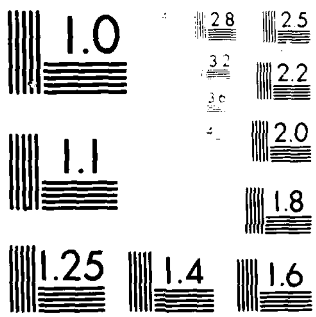
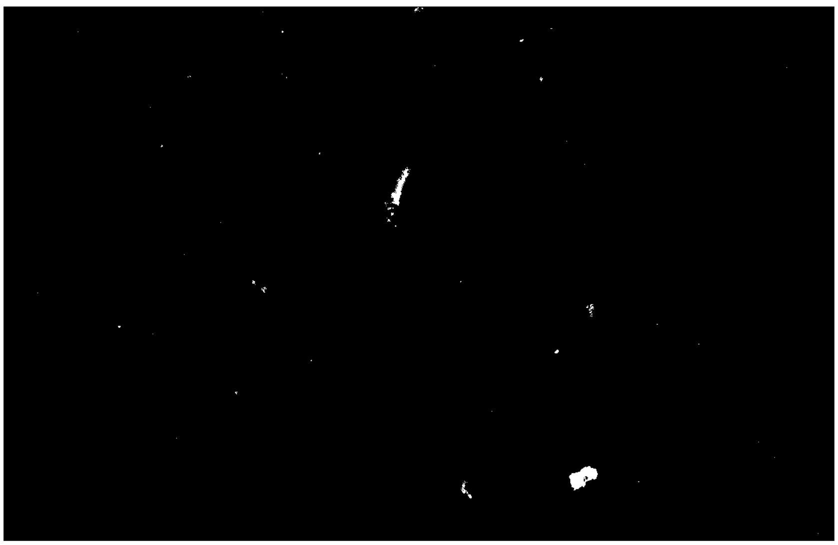




MICROCOPY RESOLUTION TEST CHART



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16. Abstract

Since 1974, the U.S. Coast Guard has been testing lead-acid batteries in solar photovoltaic-powered systems for aids to navigation. Three types of lead-acid batteries, distinguished by the composition of their grid material, have been tested: lead-antimony grid, lead-calcium grid, and pure-lead grid.

This report contains a comparison of the charging characteristics and the charge-discharge cycling behavior of each grid type. All types were remarkably similar qualitatively in their daily as well as annual cycling behavior but the significance of the quantitative differences offer distinctive tradeoffs.

This report presents models for water usage, depth-of-discharge, and post-cycle capacity for various levels of voltage regulation. Based on the post-cycle capacity tests, the effect of grid strength, grid thickness, and operating conditions on life expectancy are presented.

A final discussion presents the results of a field deployment of solar photovoltaic-powered aids to navigation in the Miami, Florida area. Potential solutions to the battery terminal corrosion and bird guano problems observed are discussed.

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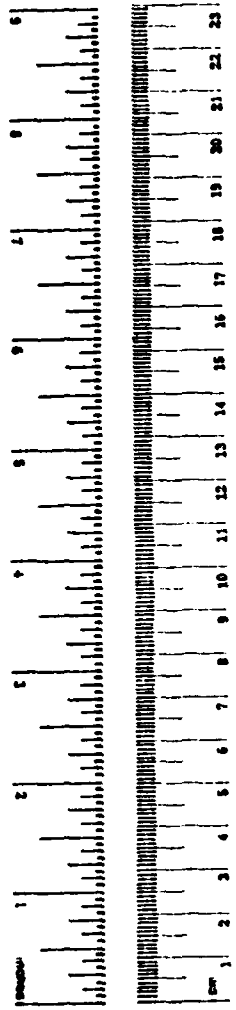
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

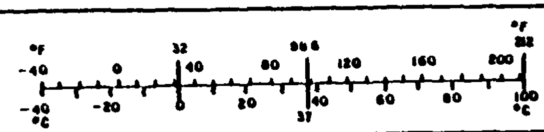
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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1.0 INTRODUCTION

Batteries serve as the power source for nearly all of the over 14,000 lighted aids to navigation maintained by the United States Coast Guard. For nearly 20 years, primary batteries (i.e., non-rechargeable) of the zinc-carbon air-depolarized type have been successfully used for aids to navigation service. With proper maintenance and replacement, for which schedules are well established, these batteries provide highly reliable performance. Notwithstanding, these batteries are becoming less attractive due to rising replacement costs, restricted availability, and increasing disposal difficulties caused by environmental concerns, particularly mercury contamination.

Solar energy is the leading alternative natural power source and the heart of virtually every solar photovoltaic energy system in existence is a secondary, rechargeable battery. For about seven years, the U.S. Coast Guard Research and Development Center has been actively studying secondary batteries in solar photovoltaic energy applications; these efforts are dis- cussed in this paper. The complete battery research program can be conve- niently divided into three distinct but overlapping test phases: exploratory testing, voltage regulation testing, and life expectancy testing.

Exploratory testing began in early 1974 as a part of research efforts directed at developing a solar photovoltaic energy system for aids to navigations. In all, 53 separate systems were placed in operation, each consisting of a solar array, a lead-acid storage battery, flashing light, and, in some cases, a voltage regulator (figure 1-1). The basic purpose was to evaluate the individual components and to ascertain the system reliability in aids to navigation operation. Preliminary results indicated several areas where information was incomplete or totally lacking; thus, the scope of inquiry was broadened to include investigations of voltage regulation parameters.[1]

Building upon the experience gained from the exploratory phase, a new phase of investigation was initiated to evaluate the suitability of zener diodes as voltage regulators, the optimum regulation point, and expected water usage in liquid electrolyte lead-acid batteries. Voltage regulation testing was initiated in September 1975 using 15 new photovoltaic systems assembled from usable components of the exploratory phase systems. Three groups of five identical systems, each using arrays with predictable outputs, two regulated groups using different voltage levels and one unregulated group were placed in operation.

During the voltage regulation testing, it became evident that there was a need for data to predict the life expectancy of batteries in solar power applications. Accordingly, life expectancy testing was begun in the summer of 1978 using a standard two-level factorial experimental design as the fundamental method. Voltage regulation and battery discharge depth were the independent variables used for measuring the effects on battery life. This design also permitted an attempt at establishing the relationship between regulating voltage and water usage. In June 1981, all testing was terminated with all batteries (ranging in age from three to seven years) removed for post-cycle capacity tests to determine their condition for life expectancy estimations.

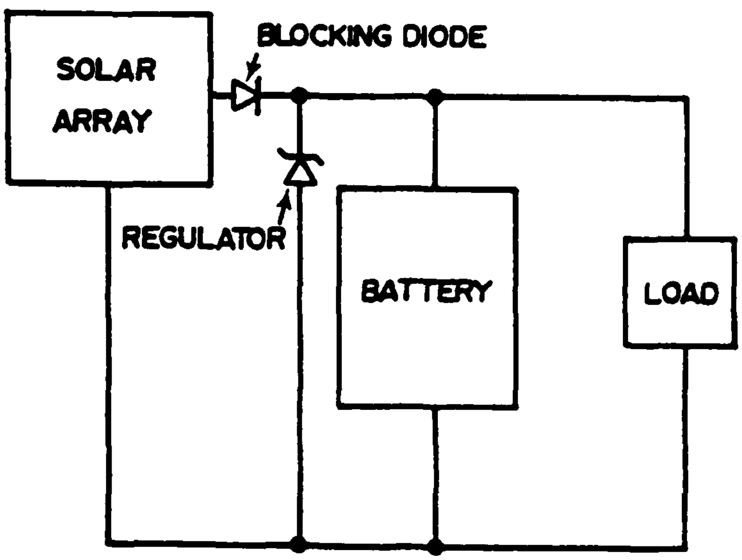

FIGURE 1-1

General Configuration of the Solar Photovoltaic Energy for Aids to Navigation

The exploratory testing, voltage regulation testing, and preliminary results of the life expectancy testing have been previously reported in the interim report "Evaluation of Solar Photovoltaic Energy Storage for Aids to Navigation," CG-D-5-81, ADA096476, November 1980. The reader is referred to this report for a general overview of lead-acid battery behavior and a detailed analysis of the exploratory and voltage regulation testing. This final report will present the highlights of the previous testing. Its primary focus will be on the life expectancy testing with an emphasis on the evaluation of the condition of all batteries which had undergone long-term cycling in solar photovoltaic systems.

2.0 PHOTOVOLTAIC SYSTEM DESIGN

In a solar photovoltaic power system for an aid to navigation, the secondary (i.e., rechargeable) battery acts as a reservoir of energy to operate the aid during periods of darkness. During the daylight hours the array either fully or partially recharges the battery depending upon array size and the availability of solar energy (insolation). There are two distinct cyclic demands placed on the battery. One is relatively "shallow" but highly repetitive charge-discharge with a frequency of one cycle per day. The second discharge cycle is a long-term gradual deep discharge on a one cycle per year basis (figure 2-1).

The Coast Guard has developed a computer model which predicts the lowest battery state-of-charge during the long-term, deep, annual discharge cycle. The model requires the following inputs: average monthly insolation, a straight photovoltaic efficiency, a load based on average hours of darkness, and a complex battery storage efficiency.[2]

The overall, or round trip, energy efficiency of a lead-acid battery is approximated by the product of the ampere-hour and voltage efficiencies. These are dependent on both cell design and operating conditions. Ampere-hour efficiency (electro-chemical efficiency) is the ratio of the ampere-hours' output to the ampere-hours of the recharge. This can also be called charge storage efficiency. Voltage efficiency is the ratio of the average voltage during the discharge to the average voltage during the recharge. In photovoltaic systems, knowledge of the charge efficiency is essential in predicting how much of the solar array output is stored for later use. Information compiled at the R&DC indicates that the charge storage efficiency of lead-acid batteries in aids to navigation photovoltaic systems is on the order of 98-99%.

A function was developed to describe this efficiency from a comparison of computer modeled systems to actual system behavior. A charge storage efficiency function of the form

$$E = 1.58\ (1 - e^{-(1-C)^{0.1}})$$

where E = fraction of amperes stored
C = state-of-charge/100

was adopted. It provided accurate predictions for the behavior of several lead-acid batteries in photovoltaic systems.[3]

In practice the computer model is utilized to size the solar array and the battery. In all design configurations studied, the predicted depth-of-discharge during the annual cycle was limited to 50 percent. By limiting the depth-of-discharge to 50 percent, the following things are accomplished:

a. The electroylte sulfuric acid specific gravity remains high enough that the possibility of freezing is diminished. At 50 percent depth-of-discharge, the freezing point of sulfuric acid is -28^{o}C.
b. Battery cycle life is increased by avoiding deep discharges.[4]
c. A safety factor is provided to account for extended periods of below-average insolation or insolation which is less than the reference station used in the design.

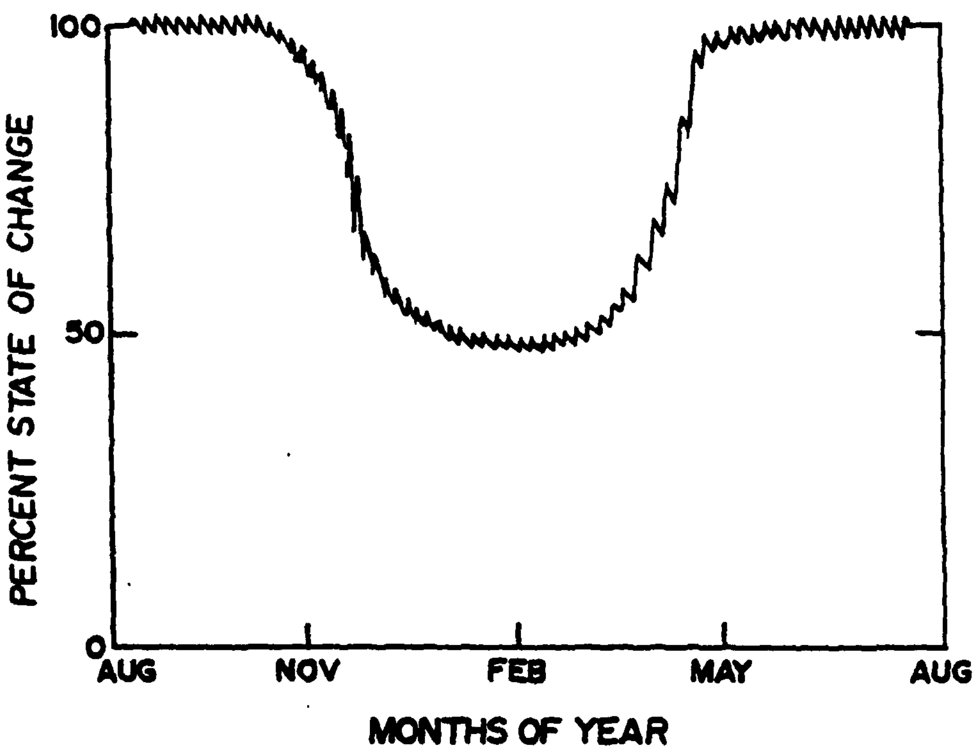

FIGURE 2-1

Yearly State-of-Charge Profile for a Secondary Battery in Solar Photovoltaic Aids to Navigation Usage

3.0 SELECTION OF BATTERY TYPE

The lead-acid battery is the only type being considered at present for solar photovoltaic systems. The choice of lead-acid batteries was made initially because of their low cost and Coast Guard's familiarity with them as a type. Later, in a study done for the Coast Guard 5 in which more than a dozen battery types were considered for solar photovoltaic system applications, lead-acid batteries were found to be best suited to the Coast Guard's needs.

The nickel-cadmium battery was second in terms of suitability. It is superior to lead-acid in expected life and cold-weather performance; however, its drawbacks are high cost, high self-discharge, and a very low charge storage efficiency at low charging rates.[6]

3.1 Lead-Acid Battery Types

There are several different types of lead-acid batteries which are distinguished by the composition of their grid. The grid is the lattice structure that holds and makes electrical contact with the active material of the battery plates. The grid is made of lead, usually alloyed with another metal for added strength and hardness. There are four types of grid construction presently available with a fifth under development. They are lead-antimony, lead low-antimony, lead-calcium, and pure lead, with lead-strontium possibly in the future. Only three types of lead-acid batteries have been tested by the Coast Guard. Each type is listed below with its salient advantages and disadvantages.

a. Lead-Acid (Antimony Alloy Grid) - Advantages: very low cost; moderate maintenance; high scrap value; high grid strength; moderate life; very good availability. Disadvantages: very high self-discharge; moderately sophisticated voltage regulator required; poor high and low temperature performance; can be destroyed if frozen; requires boost charging at regular intervals during storage; may experience sulfation if allowed to remain in discharged state; overcharge may produce grid corrosion; high gassing rate on overcharge.

b. Lead-Acid (Calcium Alloy Grid/Vented) - Advantages: low cost; low maintenance; shelf life approximately five times that of lead-antimony grid battery; high scrap value; moderate grid strength; good availability. Disadvantages: may experience sulfation if allowed to remain in discharged state; poor high and low temperature performance; can be destroyed if frozen.

c. Lead-Acid (Pure Lead Grid/Charge Retaining) - Advantages: moderate cost; long life; low maintenance; high scrap value; excellent charge retention; withstands prolonged periods without recharge. Disadvantages: low grid strength; available only in 6-volt units from one manufacturer; sensitive to overcharge, vibration, and shock; poor high and low temperature performance; can be destroyed if frozen; can spill electrolyte; maintenance water must be pure.

4.0 EXPLORATORY TESTING

In early 1974, a total of 53 systems, generally configured as shown in figure 1-1, were installed on a rooftop facility at Groton, Connecticut. The location, adjacent to Long Island Sound, served to simulate the marine environment. Eighteen systems had voltage regulation. The batteries used are described in table 4-1.

TABLE 4-1

DESCRIPTION OF BATTERIES USED IN EXPLORATORY TESTING

Manufacturer:	Gates	Gates	Globe	Globe	Wisco	Wisco
Manufacturer Designation:	(Special Purchase)	(Special Purchase)	GC12200 Type A	GC12200 Type A	DA-2-1	DD-3-3
Voltage:	12	12	12	12	12	12
Capacity (Ah):	30	60	40	60	26	100
Grid Construction	Pure lead	Pure lead	Lead-Calcium	Lead-Calcium	Pure lead	Pure lead
Electrolyte	Liquid contained in porous separator material	Liquid contained in porous separator material	Jellied	Jellied	Liquid	Liquid
Number Installed:	9	12	10	4	6	12

Although there were expectations of at least a six-year life for system components at the onset of exploratory testing, only two of the original systems operated the full seven years. Twenty-five batteries were lost during the first two years of operation because the solar arrays associated with them failed. The six 26Ah Wisco batteries were found to be unsuitable for the intended application because of high water usage and were removed from the test during the second year. Of the batteries in systems whose solar array did not fail outright, only three batteries survived two years with a capacity of 80% or better (the generally accepted minimum capacity before declaring battery failure). Two of these batteries were 100Ah pure-lead grid Wisco batteries and one, a 40Ah lead-calcium grid Globe battery. These same two 100Ah Wisco batteries operated until testing was terminated in June 1981. The Globe battery failed in the third year.

4.1 Sulfation

One of the major outcomes of the exploratory testing was an indication of potential battery sulfation problems. Crystals of lead sulfate form at both the positive and negative plates of lead-acid batteries due to the

discharge reaction. Technically, the overall process is known as sulfation, and it occurs in three characteristic ways: (1) fine sulfate crystals form as a natural part of the discharge process, (2) sulfate forms as a result of localized action or self-discharge of the plates (due to parasitic currents or acid action on the plate materials), and (3) large crystals or crusts of sulfate form as a result of neglect or misuse. The term sulfation is most commonly used to describe this last process. The effects of the first two processes are normally reversed by the charging current and are not sources of trouble. The last process, known as "Ostwald Ripening," can result in both temporary and permanent damage to the plates.[7] Excessive sulfation of the third kind is difficult to reduce. It comes from (1) allowing the battery to stand in a discharged condition for a considerable time, (2) operating the battery for prolonged periods of time at partial states of charge, (3) neglecting to make repairs when evidence of trouble within the cells becomes apparent, (4) filling the cells with electrolyte when water should have been used, (5) operating the battery at excessive temperatures, and (6) persistent undercharging. The aids to navigation application with the prolonged periods of operation in a partially discharged state (figure 2-1) runs the risk of sulfation. Prolonged operation in the summer near 100% state-of-charge tends to counter this risk. Experience at the R&D Center has shown that the positive plate grid thickness is critical to withstanding sulfation effects. In the exploratory testing, the thick plate (0.62 inches) pure-lead Wisco batteries had much longer lifetimes of usage (five times) than the thin plate lead calcium (0.11 inches) Globe batteries and thin-plate (0.06 inch) pure-lead Gates batteries. In other testing, four years of use have been obtained with C&D lead calcium batteries with thick positive grids (0.266 in). It is believed that a sulfate barrier forms around the positive grid of the thin grid lead-calcium batteries causing a severe capacity loss. This behavior was first reported by Tudor, Weistuch, and Davang.[5] They observed that lead-calcium batteries with grids of thickness (0.093 inch) were vulnerable to sulfate barrier formation while batteries with grids of 0.25 inches or greater were not. Batteries in our application appear to be susceptible to sulfate barrier formation; consequently, a positive grid thickness greater than 0.25 inches should be specified for procurement.

4.2 Self-Discharge

Another major outcome of the exploratory testing was a discounting of battery self-discharge effects. Self-discharge is a phenomenon caused by parasitic electrochemical reactions taking place within a charged cell, reducing its stored energy with an increase in time. Originally, self-discharge was considered to be an additional external load on the system which would have to be balanced by increasing the generating capacity of the array. Experience with high self-discharge and low self-discharge batteries operating in solar photovoltaic aids to navigation indicates that self-discharge is not a significant load factor.[9] A battery operating in a quiescent situation could be susceptible to self-discharge. However, in aids to navigation usage, the battery is rarely in a no-load situation. During the daylight hours, it is receiving charge from the solar panel. During the night hours, it is constantly under load from the lamp control circuitry and receives additional loading when the lamp radiates. Self-discharge is important in shelf life and storage considerations.

5.0 VOLTAGE REGULATION TESTING

During exploratory testing, a marked difference in water usage between regulated and unregulated systems was noted for one type of liquid electrolyte battery. The variance in voltage from the regulators combined with poorly performing arrays made evaluation of voltage regulator effectiveness very difficult. These results in conjunction with the early failure of some systems led to the initiation of new tests focusing more carefully on voltage regulation. A comprehensive study of voltage regulators accomplished in the summer of 1975 indicated a simple one-element voltage regulator such as a zener diode regulator was a likely candidate.[10] Accordingly, a total of fifteen new systems were placed in service during August and September 1975 to test the effectiveness of zener diodes as voltage regulators. There were five identical systems at each of the following: 13.8V regulation, 13.1V regulation, and unregulated. All systems used two 6V, 100Ah Mule lead-acid batteries (Model 6MLG-11), with lead-antimony plates and liquid electrolyte, under identical loads. Maximum solar array charge current was about 0.55-0.58A. The array-load combination used was predicted to have a 10% DOD (for unregu- lated systems) at the worst time of the year and was designed to produce about 500 Ah of excess energy per year; these conditions were imposed to accentuate the differences in voltage regulation provided by the 13.1V, 50-watt and 13.8V, 50-watt zener diodes used. There were five systems at each of the three configurations at the onset of the experimentation.

Twelve systems continued to operate until the experiment was terminated in June 1981. Two systems failed due to a cracked battery case; the third system failed due to a solar panel failure. Although the cause of the cracked-case failures is unknown, it is suspected that a failing cell in the battery developed low specific gravity which allowed it to freeze in the winter and a cracked battery case resulted. Table 5-1 is a compilation of the six-year performance of the lead-antimony grid batteries in the voltage regulation testing.

5.1 Water Usage

This avenue of inquiry sought to measure voltage regulator effectiveness with water usage and specific gravity as dependent variables and level of voltage regulation or lack of any regulation (i.e., 13.1V, 13.8V, and unregulated) as the independent variables. Water usage provides a measure of the effectiveness of voltage regulation in reducing overcharge of the battery as 3 ampere-hours of overcharge disassociates 1 ml of water per cell in the battery. Annually, during April, the batteries were refilled with water and the average amount added to the batteries in each configuration is listed in table 5-1. Annual variations in insolation are responsible for the large standard deviation of the data points.

The voltage regulators were very successful in reducing water usage. The average water usage of the 13.1-volt systems indicates that 20 years of operation is possible before water would have to be added to the battery. The 13.8-volt systems would allow 10 years, while the systems with no regulator would allow only 2.5 years before water replenishment would be necessary.

TABLE 5-1

Voltage Regulation Testing Results

GRID MATERIAL	LEAD-ANTIMONY	LEAD-ANTIMONY	LEAD-ANTIMONY
SYSTEM AGE (YR)	6	6	6
RESERVE ELECTROLYTE (ML)	1860	1860	1860
NUMBER OF SYSTEMS	5	5	5
REGULATOR TYPE	None	Shunt Zener Diode	Shunt Zener Diode
REGULATION LEVEL (VOLTS)	Unregulated	13.8	13.1
AVERAGE ANNUAL WATER USAGE (ML)	690.43 (87.89)	181.16 (60.26)	98.98 (45.32)
AVERAGE WATER REPLENISHMENT CYCLE (YR)	2.5	10.0	20.0
DESIGNED DEPTH-OF-DISCHARGE (%)	10	10	10
ACTUAL DEPTH-OF-DISCHARGE (%)	8 (4)	32 (6)	65 (12)
AVERAGE POST-TEST CAPACITY (%)	+14 (12.8)	+6 (4.6)	-13 (6.24)
NUMBER OF FAILURES	2	0	1
TIME TO FIRST FAILURE (YR)	3	6+	2
FAILURE TYPE	Cracked Case		Cracked Case
PROBABLE FAILURE CAUSE	Low Specific Gravity of a Failing Cell; solar array failure		Low Specific Gravity of a Failing Cell

Standard deviations of the data shown in parenthesis.

5.2 Depth-of-Discharge

Quarterly, the specific gravity of the batteries, a means of monitoring the state-of-charge of a battery, was recorded to ascertain the effect of the voltage regulation on the computer predicted depth-of-discharge of the system. Ideally, the regulator would allow all energy to enter the battery when the battery is at less than 100 percent state-of-charge. In fact, regulators do not operate perfectly. How imperfectly they work can be ascertained by observing the depth-of-discharge to which the system falls during the winter months. This is possible as, during the fall months, the photovoltaic system operates generally in a deficit energy situation (i.e., energy going into the load is greater than what is being generated by the array). If a regulator rejects energy, the energy deficit cannot be made up by the array due to the continually decreasing insolation and must be made up by the battery which has to go to a greater depth of discharge to produce it. Table 5-1 lists the average annual depth-of-discharge observed for the systems in the voltage regulation testing.

The unregulated system dropped on an average to 8 percent depth-of-discharge during the winter which is very close to the 10 percent designed depth-of-discharge predicted by the computer model. The 13.8-volt systems dropped to 32 percent depth-of-discharge which indicates that the regulator rejected 22 ampere-hours of charge. The 13.1-volt systems dropped to 65 percent depth-of-discharge which indicates that the regulator rejected 55 ampere-hours of charge. The 13.1-volt system exceeded the 50 percent depth-of-discharge limit risking freezing of the electrolyte and a catastrophic failure. With the addition of a regulator in the system, the computer model must be modified to predict a greater depth-of-discharge as has been observed.

5.3 Post-Cycle Capacity

Prior to placing the Mule batteries in systems for the voltage regulation testing, each battery was cycled twice and its initial capacity measured. The pre-test conditioning included two cycles consisting of a 2.5 ampere constant current charge to a fixed voltage of 14.7 volts followed by a 2.5 ampere constant current discharge to 10.5 volts. The capacity was recorded on each discharge.

At the termination of testing, all batteries where fully charged in the laboratory and then discharged to measure their post-test capacity. Again, the voltage regulation level had a significant effect. The batteries that had received no regulation were in excellent condition; the post-test capacity was 14 percent higher than their initial capacity. For the 13.8-volt system, the post-test capacity was 6 percent higher while the 13.1-volt systems had a 13 percent decrease in capacity. The capacity increases can be attributed to incomplete grid formation during the pre-test conditioning. The poorer condition of the 13.1-volt systems probably can be attributed to the greater depth-of-discharge at which those systems cycled. The greater depth-of-discharge means longer stands (up to 5 months) in a partially discharged state probably causing sulfation.

As Mule batteries had clear cases, it was possible to observe the amount of material that had eroded from the grids. Overcharging a battery can cause significant grid erosion and eventual failure. The unregulated systems

which had received considerable overcharging did not appear to have grid erosion significantly greater than the other systems. In all cases, grid erosion was minor indicating many more years of cycling was possible with these batteries before grid erosion would be significant.

5.4 Conclusions

Zener diodes are known to have less than optimal temperature characteristics for voltage regulation of lead-acid batteries.[11] Their behavior is representative, however, of the problems encounter in voltage regulation and the tradeoffs involved in selecting a voltage regulation point. Other regulators with better temperature characteristics, ect., are subject to the same problems and tradeoffs to varying degrees. All regulators should be tested at the system level with a solar array and battery to determine the magnitude of the tradeoffs involved with their utilization.

The voltage regulation testing clearly points out the tradeoffs in selecting a voltage regulation point. The selection of lower voltages means less overcharge and lower water use, but with lower voltage limits more energy that could go into the battery gets dissipated or rejected by the regulator. This causes the battery to recharge at slower rates and dip to greater depths-of-discharge risking sulfation damage.

Although lead-antimony grid batteries were not considered to be the optimum choice for a photovoltaic energy system, the voltage regulation testing demonstrated that they are capable of operating at least six years in aids-to-navigation usage. Due to the difficulty in regulating lead-antimony batteries (Section 7.0), the system designer is forced to decide between low water usage which extracts a penalty of great depth-of-discharge risking sulfation and shortened life or high water usage with more frequent water addition but longer battery lifetimes.

6.0 LIFE EXPECTANCY TESTING

The experience derived from the exploratory and voltage regulation testing phases suggested the need for a means to predict the life expectancy of batteries in solar photovoltaic energy applications. Accordingly, in the summer of 1978, additional testing was initiated. The stated objective was to define the effects of overcharge (i.e., voltage regulator level) and depth-of-discharge on battery water replenishment and battery life.

6.1 Experimental Design

To examine the effects of overcharge and depth-of-discharge (DOD), a standard, two-level, factorial experiment was conducted following the procedures set forth in DuPont's Strategy of Experimentation. Response surface curvature was gauged by employing a center point in the design.[12] A total of 23 systems were assembled, each was comprised of a solar array, a non-temperature compensated zener diode voltage regulator where required, a battery, and a load. The number of systems, the regulating point, and the load description were as follows:

NUMBER OF SYSTEMS	VOLTAGE REGULATING POINT	LOAD DESCRIPTION	DOD[1]
4	14 Volts	0.55 A lamp, 10% duty cycle	10
4	Unregulated	0.55 A lamp, 10% duty cycle	10
4	14 Volts	0.77 A lamp, 10% duty cycle	50
4	Unregulated	0.77 A lamp, 10% duty cycle	50
7 (center point)	15 Volts	0.55 A lamp, 12% duty cycle	30

[1]Predicted by computer model without accounting for effects of regulation.

Commercially available, 36-cell, ten watt, solar arrays were employed. All batteries used in the basic test matrix were new Wisco Type DD-3-3, 6V, 100Ah units in a 12V, 100Ah configuration. In addition, five 80Ah C&D lead-calcium batteries were altered to match the operational factors of the center point, permitting limited comparisons between them and the Wisco pure lead batteries. Water usage and specific gravity were the dependent variables analyzed. The predicted depth of-discharge was obtained by varying the amperage and duty cycle of the load in the system design computer model.

A second test incorporated a temperature-controlled zener diode voltage regulator (TCR) on a total of 8 additional systems as follows:

NUMBER OF SYSTEMS	VOLTAGE REGULATING POINT	LOAD DESCRIPTION	DOD
4	14 Volts (TCR)	0.55 A lamp, 10% duty cycle	10
4	14 Volts (TCR)	0.77 A lamp, 10% duty cycle	50

The TCR incorporates a thermal switch in series with the zener diode regulator. The switch opens the circuit to the zener diode at $2 \pm 2^{o}C$ and closes at $10 \pm 2^{o}C$. For the Groton, Connecticut test site, these temperature settings ensure unregulated operation from November to March eliminating energy losses through the regulator while providing for regulated operation during the summer months preventing water usage.

6.2 Method of Analysis

Use of Strategy of Experimentation provides the philosophic and practical elements of experimental strategies, as well as the methodology of statistical experimental design, in a "cookbook" format. In particular, the general model underlying the two-level factorial used in life expectancy testing is

$$y = b_0 + b_1X_1 + b_2X_2 + \ldots + b_pX_p + b_{12}X_1X_2 + b_{13}X_1X_3 + \ldots\ldots + b_{p-1,p}X_{p-1}X_p + \text{higher order interactions}$$

where y = predicted response = dependent variable
X_p = pth factor = pth independent variable
b_p = pth factor effect
b_{p-1} = interaction effect for X_pX_{p-1}
b_0 = mean

The step-by-step approach yields a prediction equation tested for response surface curvature with only the significant factors and interaction effects included (i.e, coefficients greater than variability of data). The equation can then be interpreted in terms of the independent variables used as factors.

Prior to the utilization of a linear prediction model, several limitations must be understood:

1. The prediction equation at this level of analysis can only be considered to be valid within the experimental region of the independent variables.

2. The prediction is limited to estimates of linear effects and interactions and indicates their relative importance.

3. The center point is used to estimate the curvature of the response and provides a check for the "lack of fit" of the model. If the response has significant curvature, it should be modeled by a higher-order equation. The more severe the curvature, the smaller the region around the independent variables the linear prediction will give accurate results.

6.3 Water Usage Model

Rather than analyze the water usage data for each individual year as presented in the iterim report,[13] the readings were totaled for three years to obtain a more general model. By totaling the three years, the annual variations in insolation should be averaged and the imprecisions in water addition should be minimized. The water usage modeled as a three-year total:

$$\text{Water Usage} = 191.02\ \text{ml} + 190.5\ (\text{Regulating Voltage} - 15\ \text{Volts})$$

The only significant factor in water usage was the regulating voltage. The effect of depth-of-discharge and the interaction between depth-of-discharge and regulating voltage was smaller than the variability of the data. The test for significant curvature indicated that the response could be predicted by a linear model.

As the reserve electrolyte capacity of the Wisco pure-lead grid batteries is 1230 ml, this model indicates that if the regulation point is less than 15.0 volts, at least 10 years of operation is possible before water will have to be added to the battery.

6.4 State-of-Charge Model

An analysis of the specific gravity data for February 1980 was completed to estimate the relative importance of voltage regulation on the actual state-of-charge of the system. As noted in the voltage regulation testing, the computer design model would have to be modified to compensate for voltage regulation.

The February 1980 actual state-of-charge model:

$$\text{Actual State-of-Charge } (\%) = 67.5\% - 1\%\ (\text{Designed Depth-of-Discharge} - 30) + 18.5\%\ (\text{Regulating Voltage} - 15\ \text{Volts})$$

The response surface curvature was not significant indicating that the data may be described by a linear model.

The model indicates that a change of one volt in the voltage regulation point causes an 18.5 percent change in the actual state-of-charge. Thus for Wisco batteries and shunt zener diode regulators, the computer model must be corrected by this amount.

6.5 Life Expectancy Model

Prior to the placing of the Wisco batteries into the life expectancy testing matrix, each battery was cycled twice to measure its initial capacity. At the termination of the testing, all batteries were fully charged and then discharged to measure their post-test capacity. The change in capacity over the three-year cycling test provides the basis for a model of the life expectancy of the batteries. The ratio of the post-test capacity to the initial capacity formed the data points which were entered into the two-level two-factor matrix (table 6-1). The analysis utilized the same method as the water usage data.

TABLE 6-1

Mean Post-Test Capacity (percent of new)

Depth-of-Discharge	Voltage 14V	15V	16V
10	101.75 (4.5)		106.5 (3.3)
30		104.43 (3.2)	
50	80.75 (24.2)		103.25 (8.2)

Standard Deviations of data shown in parenthesis.

The analysis yielded the following model for post-test capacity:

Post-Test Capacity (percent of new) = 98.06 - 0.30 (Predicted DOD-30) + 6.83 (V-15) + 0.23 (V-15) (Predicted DOD-30)

In this model, both the effect of the depth-of-discharge, the regulating voltage, and their interaction were significant. The test for curvature indicated that the response could be predicted by a linear model.

As expected, the model indicates that the greater depth-of-discharge a battery is cycled to and the lower the voltage regulating limit, the lower the post-test capacity. The interaction term indicates that simultaneous deep discharges and low regulating voltages place an additional penalty on post-test capacity. The low regulating voltage is important only if it means the complete elimination of overcharging of the battery. Without some over-charging as evidenced by water usage, the battery grids are not reconditioned from the deep winter discharge.

In utilizing the post test capacity model, it should be understood that more than one failure mechanism may be responsible for the behavior observed. The failure mechnanisms may be a monotomic aging mechanism which is easily modeled or a catastropic mechanism which is not easily modeled. The key to recognition of which mechanism is at work is the standard deviation of the data. Data with large standard deviations probably represent catastrophic failure mechanisms. Small standard deviations probably represent aging mechanisms.

The data and the model can be interpreted that a catastrophic failure mechanism is present when the regulation voltage is held to 14.0V and the depth of discharge is 50%. The factors interacting to cause the catastrophic failures are no overcharging coupled with deep annual discharges.

6.6 Temperature-Controlled Regulator

A second goal of the life expectancy testing was to measure the effectiveness of using ambient air temperature to control a shunt zener diode. The temperature-controlled regulator (TCR) incorporated a thermal switch in series with a shunt 14.0-volt zener diode. At $2 \pm 2^{\circ}$C, the thermal switch opens the circuit removing the shunt zener diode from the charging circuit. The switch will remain open until it reaches $10^{\circ} \pm 2^{\circ}$C. At this point, the thermal switch closes, placing the shunt zener diode across the the charging circuit. In Connecticut, these temperature switching points should allow the

system to receive no regulation in the winter months and full regulation in the summer months.

Table 6-2 is a comparison of two systems with TCR and identical systems with non-temperature-controlled shunt zener diodes. The TCR systems allowed slightly more water usage than the non-TCR systems but in both cases the average maintenance cycle was well in excess of 20 years. The TCR reduced the actual depth-of-discharge in both cases with a savings of 33 ampere-hours in the 50 percent designed depth-of-discharge systems. The reduction in actual depth-of-discharge coupled with some water usage due to overcharging shows up as an improvement in post-cycle capacity with the TCR systems showing capacities above their initial capacities after 3 years. The non-temperature-controlled 50 percent depth-of-discharge batteries are near 80 percent of initial capacity, a level that commonly defines failure. The temperature-controlled regulators were successful in controlling water usage, reducing depth-of-discharge and improving post-cycle capacity and life expectancy.

6.7 Conclusions

Linear models were developed to provide predictions of the water usage, minimum state-of-charge and post test capacity of batteries in solar photovoltaic power systems. The models apply specifically to solar photovoltaic system operating in a northern climate with non-temperature compensated zener diodes as regualtors and Wisco pure-lead grid batteries. Other locations, voltage regulators, and batteries would yield different coefficients in the models but should not alter the signs or relative magnitudes of the coefficients of the models.

The voltage regulation level was a significant term in all three models derived from the life expectancy testing. There are tradeoffs involved in selecting the regulation point. Selection of a lower voltage point reduces water usage and maintenance but it forces the battery to go to greater depths of discharge and, if coupled with no overcharging, can significantly shorten battery life expectancy by precipitating a catastrophic failure.

TABLE 6-2

Temperature-Controlled Regulator Testing Results

GRID MATERIAL	PURE LEAD	PURE LEAD	PURE LEAD	PURE LEAD
SYSTEM AGE (YR)	3	3	3	3
RESERVE ELECTROLYTE (ML)	1230	1230	1230	1230
NUMBER OF SYSTEMS	4	4	4	4
REGULATOR TYPE	NOTE 1	Shunt Zener Diode	NOTE 1	Shunt Zener Diode
REGULATION LEVEL (VOLTS)	14.0	14.0	14.0	14.0
AVERAGE ANNUAL WATER USAGE (ML)	7	0.75	9	0.25
AVERAGE WATER REPLENISHMENT CYCLE (YR)	20	20	20	20
DESIGNED DEPTH-OF-DISCHARGE (%)	10	10	50	50
ACTUAL DEPTH-OF-DISCHARGE (%)	22	28	47	80
AVERAGE POST-TEST CAPACITY (%)	+12 (10.7)	+2 (2.9)	+3 (3.2)	-19 (24.2)
NUMBER OF FAILURES	1	0	1	0
TIME TO FIRST FAILURE (YR)	2	0	2	0
FAILURE TYPE	Low Specific Gravity		Low Specific Gravity	
FAILURE CAUSE	Solar Array Failure		Solar Array Failure	

NOTE 1: Ambient air temperature-controlled 14.0-volt shunt zener diode.

Standard Deviation of the data shown in parenthesis.

7.0 COMPARISON OF BATTERY TYPES

The exploratory testing, voltage regulation testing, and life expectancy testing allow a comparison between the battery types based on their performance.

7.1 Charging Characteristics

Operating concurrently with the lead-antimony grid systems in the voltage regulation testing were two pure-lead grid systems left over from the exploratory testing. When the water usage of the unregulated pure-lead grid systems is compared to the water usage of the unregulated lead-antimony grid system (table 7-1), a significant difference is noted.

This difference in water usage illustrates that the presence or absence of antimony in the grids causes an important electrical difference in batteries. When fully charged, batteries without antimony have a much higher resistance to charge, or counter-EMF, than do the batteries with antimony in the grids. At less than full charge, they are similar. The higher resistance to charge results in a wider variation in voltage during charging allowing for a greater tolerance of overcharging and easier voltage regulation of pure-lead grid batteries. Figure 7-1 contrasts the behavior of a pure-lead grid battery and a lead-antimony grid battery. The charging voltage of an unregulated solar photovoltaic system consisting of a 10-watt solar array and a 100-Ah pure-lead grid and lead-antimony grid battery at 100 percent state-of-charge is plotted versus time of day. The voltage was sampled at 5-minute intervals throughout the day. Both systems start the day at a similar voltage. Each system begins to rise in voltage as the sun increases input current. When the solar array has replaced the energy used in the load the previous night, the charge voltage of the pure-lead system rises rapidly. This rapid voltage rise can easily be used to trigger a regulation device. The lead-antimony system does not demonstrate the voltage rise and is, therefore, harder to regulate.

Lead-calcium grid batteries are electrically similar to pure-lead batteries and exhibits almost identical charging behavior and water usage (table 7-1). The lower depth of discharge and the absence of any annual water usage indicates that the lead-calcium battery should be regulated at a higher voltage than the pure lead grid battery. With a higher regualting voltage the actual depth-of-discharge would probably be nearer the designed value.

7.2 Similarities in Cycling Behavior

The three types of lead-acid batteries tested are more remarkable in their similarities in cycling behavior than in their differences. Each type appears to have a similar charge efficiency function as the computer model could predict with reasonable accuracy the cycling behavior without regard for grid material. Self-discharge rates appear to have no effect in the annual cycling behavior. The computer model does not contain any function adjusting for self discharge. The post-test capacity of all batteries was lowered by voltage regulation which deepened the annual cycles and reduced water usage. All grid types appeared to benefit from some overcharging in the summer which reverses the effects of sulfation. In order to overcome the effects of the long stand at low states-of-charge, the grids should be thicker than 0.25 inches. Almost all failures of the batteries appear as cracked cases. This

is probably caused by a failing cell that develops a low specific gravity allowing the cell to freeze in the winter and crack the case.

In the Coast Guard application all grid types have provided satisfactory performance.

7.3 Life Expectancy

The post-test capacities illustrate several aspects of battery behavior. The seven year old WISCO pure lead grid batteries are beginning to monotonically fail due to an aging mechanism. Their reduction in capacity of over 20% and their small standard deviation would indicate an aging failure mechanism.

The lead-calcium grid batteries appear to be vulnerable to a catastrophic failure mechanism. They have a low post test capacity and a high standard deviation of the data. Their use of no water after four years of cycling indicating no overcharging is probably the reason for the catastropic failures. With a higher regulation point, the catastrophic failures of the lead-calcium batteries could probably be prevented.

In reviewing the results of all testing, these factors appear to be important to the ultimate battery life expectancy:

1. Grid Strength - Allows the battery to withstand deeper discharges and reduces grid erosion on overcharging.

2. Grid Thickness - Allows the battery to the sulfation effects from prolonged stands at less than 100 percent state-of-charge. Life may vary from 2-3 years in the case of thin plates, 6-10 years with thickness medium plates, and 17-22 years with plates of 0.25-0.35 inch thickness.[14]

3. Operating Conditions - Care should be taken to avoid deep discharges coupled with no overcharging. Both pure lead grid (Section 6.5) and lead-calcium grid (table 7-1) have demonstrated reduced post-test capacity and a vulnerability to catastropic failures under these operating conditions.

TABLE 7-1

Comparison of Battery Performance

GRID MATERIAL	LEAD-ANTIMONY	PURE LEAD	PURE LEAD	LEAD CALCIUM
SYSTEM AGE (YR)	6	7	3	4
RESERVE ELECTROLYTE (ML)	1860	1230	1230	1350
NUMBER OF SYSTEMS	5	2	7	5
REGULATOR TYPE	None	None	Shunt Zener Diode	Shunt Zener Diode
REGULATION LEVEL (VOLTS)	Unregulated	Unregulated	15.0	15.0
AVERAGE ANNUAL WATER USAGE (ML)	690.43 (87.89)	181.83 (48.08)	12.5 (29.51)	0 (0)
AVERAGE WATER REPLENISHMENT CYCLE (YR)	2.5	6.75	>20	>20
DESIGNED DEPTH-OF-DISCHARGE (%)	10	10	30	30
ACTUAL DEPTH-OF-DISCHARGE (%)	8 (4)	20 (4)	20 (5)	42 (9)
AVERAGE POST-TEST CAPACITY (%)	+14 (12.8)	-21 (9.9)	+4.5 (3.1)	-15.3 (25.0)
NUMBER OF FAILURES	2	0	0	1
TIME TO FIRST FAILURE (YR)	3	0	0	2
FAILURE TYPE	Cracked Case			Cracked Case
PROBABLE FAILURE CAUSE	Low Specific Gravity of a Failing Cell Solar Array Failure			Low Specific Gravity of a Failing Cell

Standard deviation of the data shown in parenthesis.

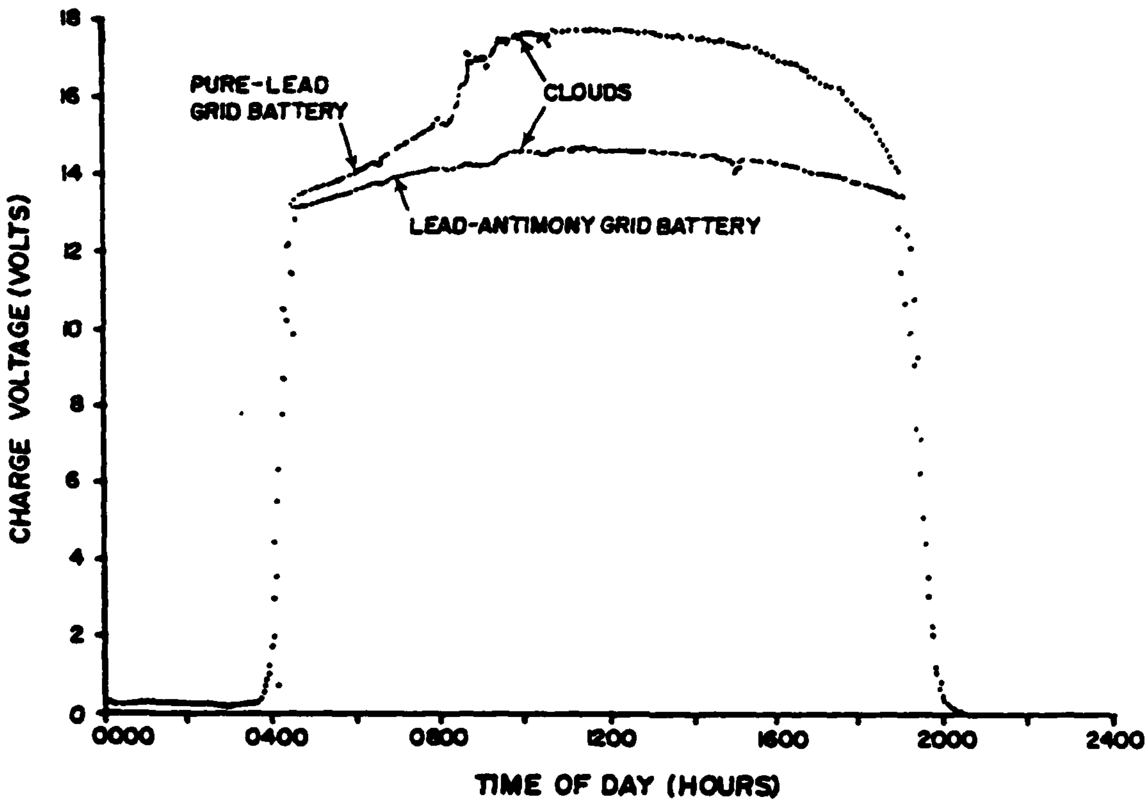

FIGURE 7-1

Charging Voltage Points (Five-Minutes Intervals) of a Pure-Lead Grid Battery and a Lead-Antimony Grid Battery in a Solar Photovoltaic Power System During Daily Operation (July 1981)

8.0 AIDS TO NAVIGATION SYSTEM RECOMMENDATIONS

The experience gained in operating solar photovoltaic systems on the rooftop at the Coast Guard R&D Center and a recently completed field evaluation allow for several observations and recommendations.

8.1 Seventh District Demonstration

Battery terminal corrosion and bird guano were the most serious problems encountered in a four-year field test of operational solar-powered aids to navigation in the Miami, Florida, area.[15] Several solutions are available to counter the effects of each problem.

Preliminary investigations into the battery terminal corrosion problem indicate two possible sources for the corrosion which is observed on the positive terminal exclusively. One source is the wicking of the sulfuric acid electrolyte up the anode, the second source is believed to be the galvanic action of dissimilar metals in contact on the terminal post. Most of the problems observed in the demonstration are believed to be the result of a poor selection of metals resulting in galvanic action. To counter the wicking of sulfuric acid:

1. Use of physical barriers to sulfuric acid wicking (i.e., nonvolatile greases or oil impregnated washers on the terminal post).
2. Use of a neutralizer on the terminal post; this material could be combined with a grease or oil.

To counter the galvanic action:

1. All solder, steel, zinc, and tin used in connecting to the terminal post should be replaced by lead, copper, or brass.
2. Use of a sacrificial anode which would corrode instead of the terminal material.

Servicing units should be prepared to do maintenance on the terminals including cleaning and replacing corrosion preventation materials during inspection cycles.

Several countermeasures are available for bird guano. They include:

1. Bird springs. Springs which are attached to the solar panel to frighten the birds away by movement.
2. Servicing units must be prepared to wash the panels during annual inspection cycles.
3. Certain panel construction techniques can be employed to minimize the effect of shadowing of the cells by bird guano. A front cover material which cleans easily by natural rainfall should be utilized. Glass is one such material. With the front plate covered by a cell shadowing material, such as guano, panels with transparent substrates are able to trap more light and output up to twice the current of panels with opaque substrates.

4. Bypass diodes can be included in the panel design. A bypass diode is a diode connected in parallel with each solar cell. When the cell becomes shadowed, the diode permits current from the unaffected cells to bypass, not be limited by, the shadowed cells. The panels open circuit voltage is reduced by the cell's normal contribution (0.6 volts/cell).

8.2 Rooftop Testing

The major results observed from the rooftop testing are:

1. All three lead-acid battery types are capable of providing adequate performance in the aids to navigation application.
2. Any battery selected should be specified to have a positive plate thickness greater than 0.25 inches to overcome sulfation effects and provide very long life.
3. Battery self-discharge in the aids to navigation application has no significant effect on the cycling behavior of the batteries. Self-discharge is still a consideration in shelf life and storage.
4. Regulation can significantly reduce overcharging and water usage in all battery types. Lead-antimony batteries are more difficult to regulate and more likely to use more water.
5. All regulators,to varying degrees, reject usable energy and add an extra load on the photovoltaic system which forces the batteries to go to greater depths-of-discharge in the winter. The mini-DIM computer model must be modified to account for the effects of voltage regulators.
6. The total exclusion of overcharging reduces the observed post-test capacities of batteries and, most likely, precipitates catastropic failures, significantly shortening battery life expectancies.

8.3 Conclusions and Recommendations

The emphasis of the R&D Center work has been on controlling overcharge to reduce water consumption and maintenance. This report indicates that the complete elimination of overcharging significantly reduces the battery life expectancy. As periodic maintenance on the solar photovoltaic power system (i.e., cleaning panels, battery terminals corrosion prevention, mooring inspection, etc.) will still be necessary for other than water addition to the batteries, it is recommended that the water usage goals be relaxed and periodic water addition be programmed into the maintenance cycle.

If future research is able to prevent battery terminal corrosion, reduce the frequency cleaning for bird guano build-up and lengthen the mooring inspection period, then the water frequency addition should be re-examined. Recombination caps which are designed to limit water usage by using a catalyst to recombine the hydrogen and oxygen generated during overcharging are a promising solution. Unlike voltage regulators, recombination caps are not an additional electrical load on the system nor do they reject usable energy. They would allow overcharging while controlling water usage, lengthening both battery life expectancy and maintenance cycles.

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